Vessel Enhancing Diffusion Filter

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Abstract

This paper describes vessel enhancing diffusion (VED) filters implemented using the Insight Toolkit (ITK) [2]. The filters are implementation of the VED algorithm developed by Manniesing et al [4]. The VED algorithm follows a multiscale approach to enhance vessels using anisotropic diffusion scheme guided by vesselness measure at a pixel level. Vesselness is determined by geometrical analysis of the Eigen system of the Hessian matrix. For this purpose, a smoothed version of the Frangi's vesselness function [1] is formulated. Experiments were conducted to evaluate the performance of the VED filters in enhancing vessels in lung CT scan.

Contents

1   Introduction

Accurate quantification and visualization of vascular structures is critical in diagnosis and treatment of vascular diseases. Success of interventional clinical procedures such as bypass surgery and coronary artery stenting require accurate visualization of vascular structures during the planning stage. Similarly, effectiveness of diagnostic procedures such as stenosis grading depends on accurate quantification of the vascular structures.

Various vascular imaging techniques are deployed in clinical practices. Among two dimensional techniques, Digital Subtraction Angiography(DSA) have been the most commonly used technique for visualization of blood vessels. However, slowly three dimensional imaging techniques such as CTA (Computed Tomography Angiography) and MRA (Magnetic Resonance Angiography) are becoming the imaging technique of choice in clinical settings. Vessel segmentation algorithms are often applied to volumetric data produced from these modalities. For this purpose, several segmentation techniques have been extensively developed [3]. To increase the effectiveness of segmentation algorithms, vessel enhancement procedures are often first applied to images containing vascular structures as a preprocessing step. Consequently, the performance of the enhancement algorithm tremendously impact the results of the segmentation algorithm.

Furthermore, enhancement algorithms are useful for visual interpretation of 3D vascular images. Clinicians often generate maximum intensity projects (MIP) images for visual analysis of the massive amount of data produced by 3D imaging techniques. However, occurrence of overlapping non-vascular anatomical structures greatly affect visualization of vascular structures in MIP images. Moreover, small blood vessels with low contrast edges are not clearly visible in MIP images. To alleviate these problems , enhancement algorithms are first applied on the vascular images to suppress non-vascular overlapping structures and improve delineation of small blood vessels.

1.1   Overview of VED algorithm

VED algorithm is based on anisotropic diffusion scheme guided by likelihood of vesselness at pixel level. It is basically a smoothing filter with the strength and direction of diffusion is determined by vesselness measure. The likelihood of vesselness is measured by analyzing the eigen system of the Hessian matrix. Several vesselness functions have been proposed. Manniesing's VED algorithm ([4])is based on Frangi's vesselness function. For sequentially increasing magnitude size eigen values of a Hessian matrix

$$|\lambda_1| \leq |\lambda_2| \leq |\lambda_3|$$

Frangi's vesselness function is composed of three components formulated to discriminate tubular structures from blob-like and/or plate-like structure as shown in Equation 1

$$V_F(\lambda) = \begin{cases} 0 & \text{if } \lambda_2 > 0 \text{ or } \lambda_3 > 0 \\ (1 - e^{-\frac{R_A^2}{2\alpha^2}}) \cdot e^{-\frac{R_B^2}{2\beta^2}} \cdot (1 - e^{-\frac{S^2}{2\gamma^2}}) & \text{otherwise} \end{cases} \tag{1}$$

With

$$R_A = \frac{|\lambda_2|}{|\lambda_3|} \tag{2}$$

$$R_B = \frac{|\lambda_1|}{\sqrt{|\lambda_2 \lambda_3|}} \tag{3}$$

$$S = \sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2} \tag{4}$$

α, β, γ are thresholds which control the sensitivity of the vesselness measure.

However, Frangi's vesselness function is not continuous and can't be used in the diffusion process. Hence, Manniesing et al proposed a smoothed version of Frangi's vesselness function as shown below.

$$V_S(\lambda) = \begin{cases} 0 & \text{if } \lambda_2 \geq 0 \text{ or } \lambda_3 \geq 0 \\ (1 - e^{-\frac{R_A^2}{2\alpha^2}}) \cdot e^{-\frac{R_B^2}{2\beta^2}} \cdot (1 - e^{-\frac{S^2}{2\gamma^2}}) \cdot e^{-\frac{2c^2}{|\lambda_2|\lambda_3^2}} & \text{otherwise} \end{cases} \tag{5}$$

For a multiscale analysis, the vesselness function is computed for a range of scales and the maximum response is selected.

$$V = max_{\alpha_{min} \leq \alpha \leq \alpha_{max}} V_s(\lambda) \tag{6}$$

Next, a diffusion tensor is defined in such a way that diffusion is promoted along the vessel but prohibited perpendicular to the vessel.

$$D = Q\lambda' Q^T \tag{7}$$

Where Q is a matrix containing eigen vectors of the Hessian matrix and λ' is a diagonal matrix containing the following elements

$$\lambda_1' = 1 + (w - 1) V^{\frac{1}{s}}$$

$$\lambda_2' = \lambda_3' = 1 + (\varepsilon - 1) \cdot V^{\frac{1}{s}}$$

Where ε, w and S are algorithm parameters.

Using this tensor definition, a diffusion equation is formulated as follows

$$L_t = \nabla \cdot (D\nabla L) \tag{8}$$

Vascular structures will be enhanced by evolving the image according to the above diffusion equation.

2   VED Filters Design in ITK

VED algorithm implementation consists of two main parts. The first part involves implementation of filters to compute smoothed Frangi's vesselness measure for a given image. The second part involves implementation of the anisotropic diffusion filters for vessel enhancement.

2.1   Smoothed Frangi's Vesselness Measure Computing Filters

Two filters were implemented to evaluate Frangi's vesselness measure in a multiscale framework. The first filter, HessianSmoothed3DToVesselnessMeasureImageFilter computes vesselness measure at a single scale. The second filter, MultiScaleHessianSmoothed3DToVesselnessMeasureImageFilter computes the maximum vesselness response from a range of scales. To use the filter for a multiscale analysis, a user has to specify minimum, maximum sigma values and number of scales. The filter computes and selects the maximum vesselness response at exponentially distributed number of scales between the specified minimum and maximum sigma values.

These filters are derived from the `itk::ImageToImageFilter`. For each pixel, Hessian matrix is computed using the `itk::HessianRecursiveGaussianImageFilter` filter. This filter computes Hessian matrix by convolving the input image with second and cross derivatives of the Gaussian function.

The multiscale filter has the following main public methods.

  1 To set minimum sigma value

```
SetSigmaMin  ( double );
```

  2 To set maximum sigma value

```
SetSigmaMax ( double );
```

  3 To set the number of sigma steps

```
SetNumberOfSigmaSteps( int );
```

Appendix A shows an example on how to use this filter.

2.2   Anisotropic Diffusion Filters for Vessel Enhancement

The implementation of the anisotropic filters follow the finite difference solver framework. The implementation consists of two components: solver object (itkAnisotropicDiffusionVesselEnhancementImageFilter) and a specialized finite difference function object (itkAnisotropicDiffusionVesselEnhancementFunction). The solver object establishes the infrastructure for accepting input image and producing output image. In addition, the solver object uses the specialized finite difference function object to perform the diffusion equation computation at each pixel for several iterations. The solver object and the the function objects are derived from `itk::FiniteDifferenceImageFilter` and `itk::FiniteDifferenceFunction` respectively. Figure 1 shows the flowchart for the vessel enhancement diffusion algorithm. An example program that demonstrates how to use this filter is provided in appendix B.

3   Experiments and results

Experiments were conducted to test the effectiveness of the VED algorithm in enhancing vessels in a whole lung CT scan. Figure 2 shows lung CT scan used to test the algorithm.

The testing dataset is distributed as part of the source code submission to the Insight Journal. Readers are encouraged to build the source code and run the algorithm on the testing dataset. In the first experiment,

Input Image

Allocate Output

Copy input to output

Allocate update buffer

Allocate tensor image

Diffusion iterative algorithm

Postprocess Output

Vessel Enhanced Image

Initialize Iteration

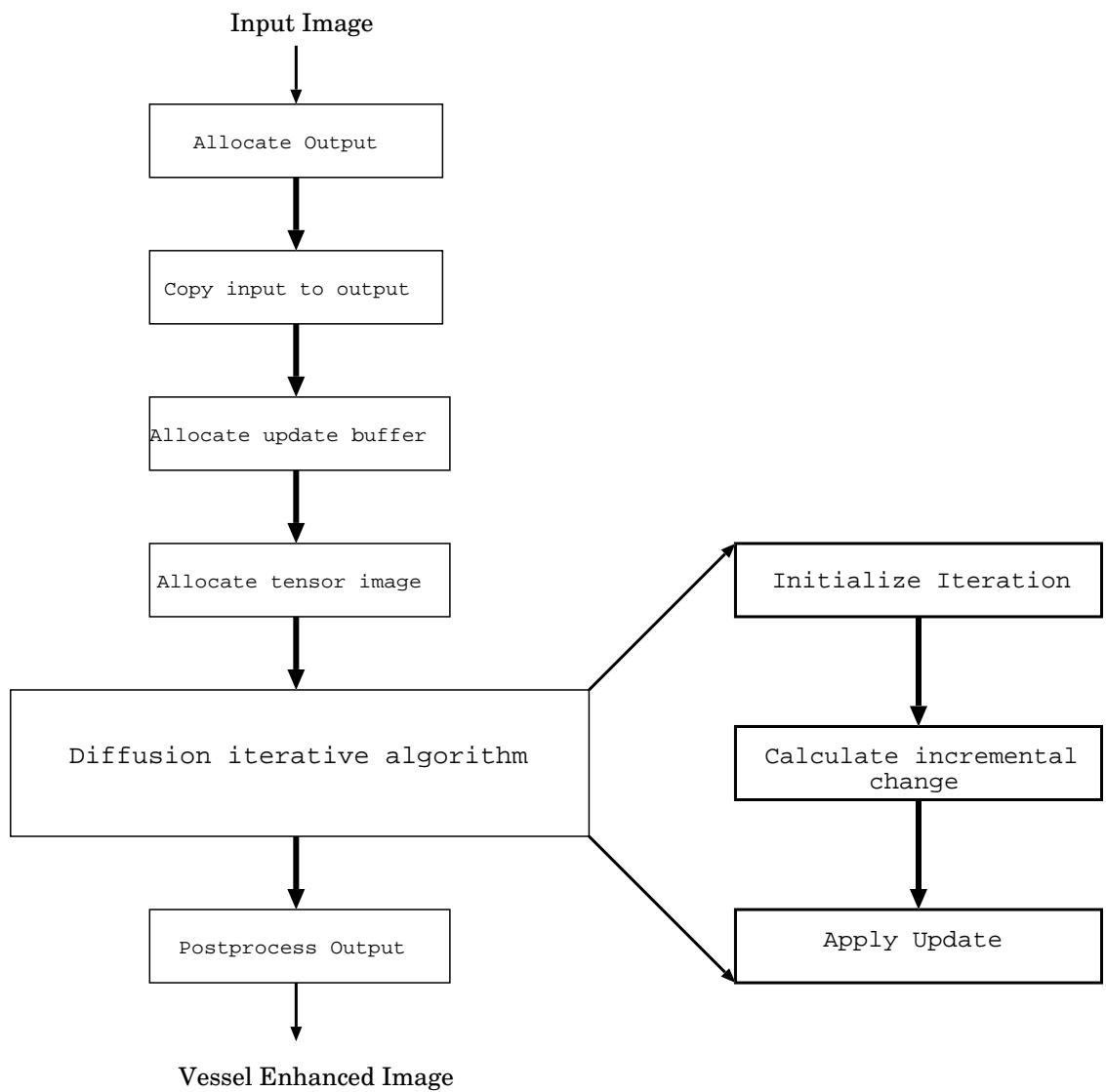Calculate incremental change

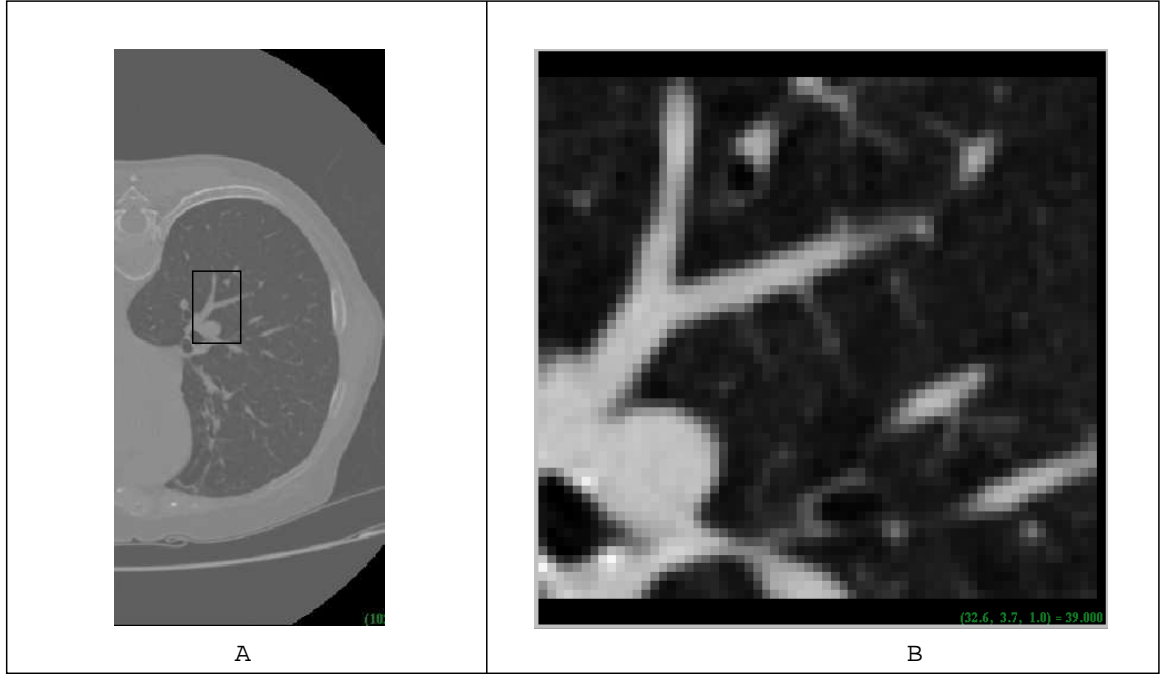Apply Update

Figure 1: VED ITK filter flowchart

Figure 2: Testing dataset: A) Lung CT scan B) Cropped ROI

Frangi's vesselness filters were run on the testing dataset to evaluate the performance of the filter on a single scale and a range of scales. The results are shown in Figure 3. With a sigma value of 0.5, small size vessels are enhanced as shown in Figure 3B. If the scale is increased to a sigma value of 4.0, large size vessels are enhanced (Figure 3C). To enhance vessels with varying size, the image was run through Frangi's multiscale filter with a sigma range of [0.5 4.0]. The result is shown in Figure 3D. As clearly evident from the result, multi scale analysis is useful in enhancing various size vessels available in the scan. This is very useful for a complete vascular structure enhancement and reconstruction. Although the vascular structures are generally enhanced, , the results show that the vesselness measure is highly sensitive to noise pixels.

In the second experiment, the performance of the VED filters was evaluated. VED filter was run on the same Lung CT scan. The results are shown in Figure 4. The VED filter was operated in a multiscale framework with computations at 10 sigma values exponentially distributed in sigma value range [0.5 4.0]. The diffusion process was analyzed for different number of iterations. The results for 10, 25 and 50 number of iterations is shown in Figure 4B, 4C and 4D respectively. Overall, the results show that VED filters enhance the vascular structures better than Frangi's vesselness measure. In addition, VED filters are less affected by noise pixels. Furthermore, with the increase in the number of iterations, an increased smoothing effect was observed.

4 Conclusions

In this paper, we have described VED filters implemented using ITK. The implementation is based on the algorithm by Manniesing et al [4]. VED algorithm uses vesselness measure based on Hessian Eigen system to guide a diffusion process. Experiments were conducted to evaluate the performance of the filters in enhancing vessels in Lung CT scans. Visualizing the enhanced images showed that VED algorithm performs better than Frangi's vesseleness measure.
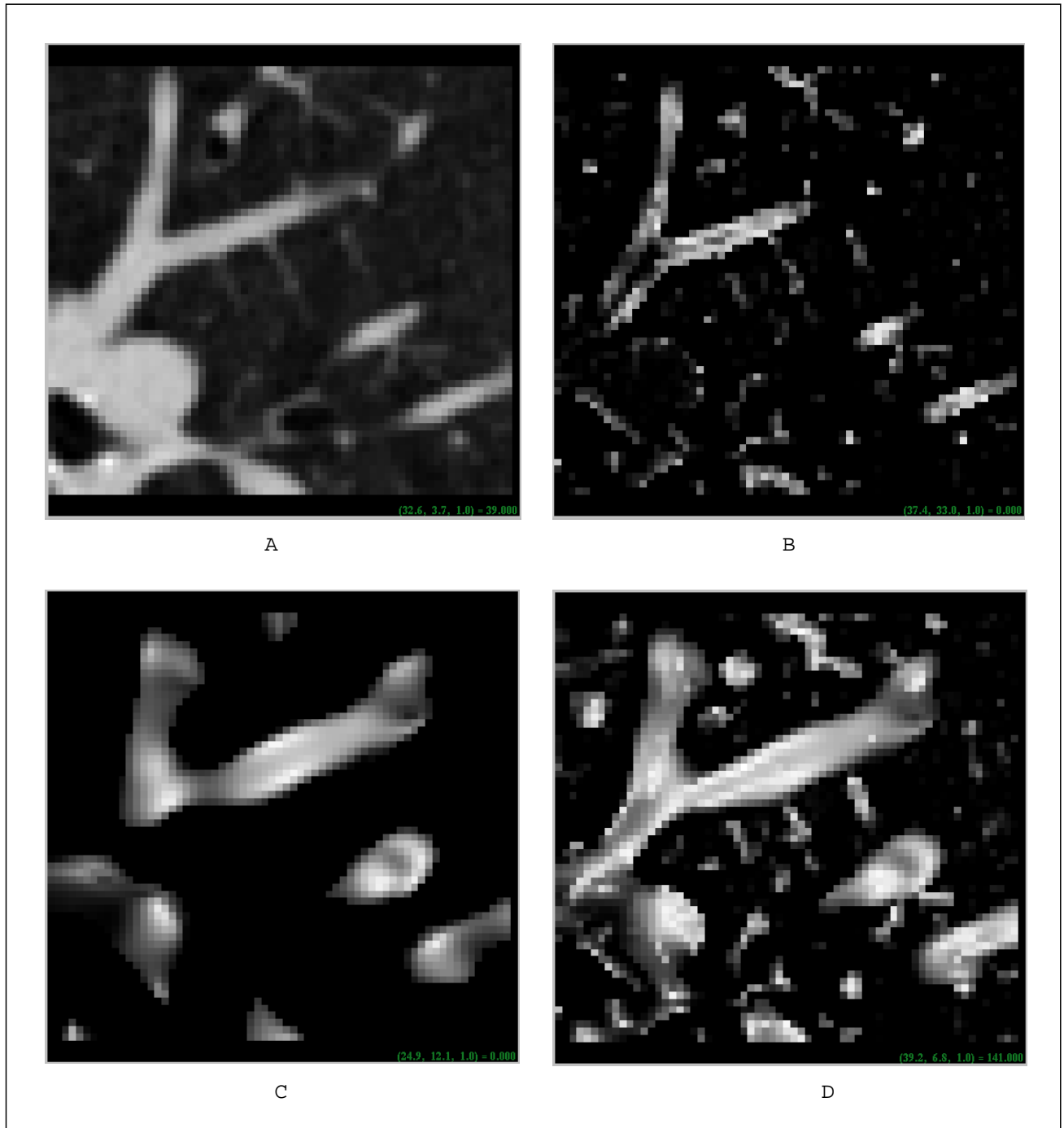
Figure 3: Frangi vesselness results: A) Original image B) sigma=0.5 C) sigma=4.0 D) Multiscale analysis sigma=[0.5 4.0]
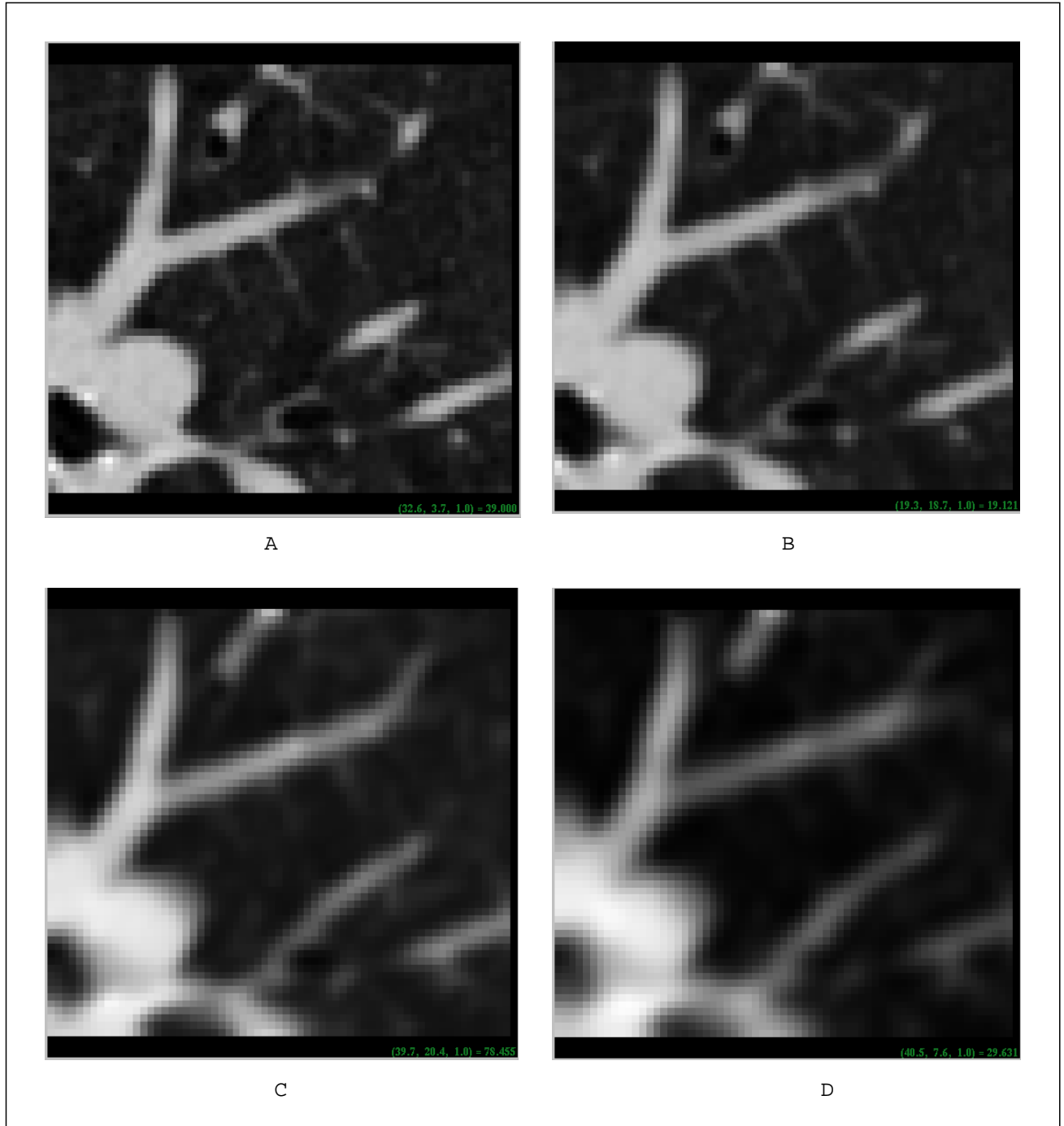
Figure 4: VED algorithm results: A) Original image B) Number of iterations = 10 C) Number of iterations = 25 D) Number of iterations = 50

5 Acknowledgment

A Example 1 - Computing vesselness measure

```
#include "itkMultiScaleHessianSmoothed3DToVesselnessMeasureImageFilter.h"
#include "itkImageFileReader.h"
#include "itkImageFileWriter.h"

#include "itkRescaleIntensityImageFilter.h"

int main(int argc, char* argv [] )
{
  if ( argc < 3 )
    {
    std::cerr << "Missing Parameters: "
              << argv[0]
              << " Input_Image"
              << " Vessel_Enhanced_Output_Image"
              << [SigmaMin SigmaMax NumberOfScales]" << std::endl;
    return EXIT_FAILURE;
    }

  // Define the dimension of the images
  const unsigned int Dimension = 3;
  typedef short       InputPixelType;
  typedef double      OutputVesselnessPixelType;

  // Declare the types of the images
  typedef itk::Image< InputPixelType, Dimension>          InputImageType;

  typedef itk::Image< OutputVesselnessPixelType, Dimension> VesselnessOutputImageType;

  typedef itk::ImageFileReader< InputImageType  >      ImageReaderType;

  ImageReaderType::Pointer   reader = ImageReaderType::New();
  reader->SetFileName ( argv[1] );

  std::cout << "Reading input image : " << argv[1] << std::endl;
  try
    {
    reader->Update();
    }
  catch ( itk::ExceptionObject &err )
```

```
  {
  std::cerr << "Exception thrown: " << err << std::endl;
  return EXIT_FAILURE;
  }


// Declare the type of multiscale vesselness filter
typedef itk::MultiScaleHessianSmoothed3DToVesselnessMeasureImageFilter<
                                    InputImageType,
                                    VesselnessOutputImageType>
                                    MultiScaleVesselnessFilterType;

// Create a vesselness Filter
MultiScaleVesselnessFilterType::Pointer MultiScaleVesselnessFilter =
                              MultiScaleVesselnessFilterType::New();

MultiScaleVesselnessFilter->SetInput( reader->GetOutput() );

if ( argc >= 4 )
  {
  MultiScaleVesselnessFilter->SetSigmaMin( atof(argv[3])  );
  }

if ( argc >= 5 )
  {
  MultiScaleVesselnessFilter->SetSigmaMax( atof(argv[4]) );
  }

if ( argc >= 6 )
  {
  MultiScaleVesselnessFilter->SetNumberOfSigmaSteps( atoi(argv[5]) );
  }

try
  {
  MultiScaleVesselnessFilter->Update();
  }
catch( itk::ExceptionObject & err )
  {
  std::cerr << "Exception caught: " << err << std::endl;
  return EXIT_FAILURE;
  }

std::cout << "Writing out the enhanced image to " <<  argv[2] << std::endl;

//Rescale the output of the vesslness image
typedef itk::Image<unsigned char, 3>            OutputImageType;
typedef itk::RescaleIntensityImageFilter< VesselnessOutputImageType,
```

```
                                              OutputImageType>
                                              RescaleFilterType;

  RescaleFilterType::Pointer rescale = RescaleFilterType::New();
  rescale->SetInput( MultiScaleVesselnessFilter->GetOutput() );
  rescale->SetOutputMinimum(   0 );
  rescale->SetOutputMaximum( 255 );
  rescale->Update();

  typedef itk::ImageFileWriter< OutputImageType  >     ImageWriterType;
  ImageWriterType::Pointer writer = ImageWriterType::New();

  writer->SetFileName( argv[2] );
  writer->SetInput ( rescale->GetOutput() );

  try
    {
    writer->Update();
    }
  catch( itk::ExceptionObject & err )
    {
    std::cerr << "Exception caught: " << err << std::endl;
    return EXIT_FAILURE;
    }

  return EXIT_SUCCESS;

}
```

B   Example 2 - Vessel enhancement using VED filter

```
#include "itkAnisotropicDiffusionVesselEnhancementImageFilter.h"
#include "itkImageFileReader.h"
#include "itkImageFileWriter.h"

int main(int argc, char* argv [] )
{
  if ( argc < 3 )
    {
    std::cerr << "Missing Parameters: "
              << argv[0]
              << " Input_Image"
              << " Vessel_Enhanced_Output_Image [SigmaMin SigmaMax NumberOfScales NumberOfI
    return EXIT_FAILURE;
    }
```

```cpp
// Define the dimension of the images
const unsigned int Dimension = 3;
typedef double      InputPixelType;
typedef double      OutputPixelType;

// Declare the types of the images
typedef itk::Image< InputPixelType, Dimension>          InputImageType;
typedef itk::Image< InputPixelType, Dimension>          OutputImageType;

typedef itk::ImageFileReader< InputImageType >      ImageReaderType;

ImageReaderType::Pointer   reader = ImageReaderType::New();
reader->SetFileName ( argv[1] );

std::cout << "Reading input image : " << argv[1] << std::endl;
try
  {
  reader->Update();
  }
catch ( itk::ExceptionObject &err )
  {
  std::cerr << "Exception thrown: " << err << std::endl;
  return EXIT_FAILURE;
  }

// Declare the anisotropic diffusion vesselness filter
typedef itk::AnisotropicDiffusionVesselEnhancementImageFilter< InputImageType,
                                    OutputImageType>  VesselnessFilterType;

// Create a vesselness Filter
VesselnessFilterType::Pointer VesselnessFilter =
                                    VesselnessFilterType::New();

VesselnessFilter->SetInput( reader->GetOutput() );

if ( argc >= 4 )
  {
  VesselnessFilter->SetSigmaMin( atof(argv[3])  );
  }

if ( argc >= 5 )
  {
  VesselnessFilter->SetSigmaMax( atof(argv[4]) );
  }

if ( argc >= 6 )
  {
```

```
   VesselnessFilter->SetNumberOfSigmaSteps( atoi(argv[5]) );
   }

if ( argc >= 7 )
   {
   VesselnessFilter->SetNumberOfIterations( atoi(argv[6]) );
   }

VesselnessFilter->SetSensitivity( 5.0 );
VesselnessFilter->SetWStrength( 25.0 );
VesselnessFilter->SetEpsilon( 10e-2 );

std::cout << "Enhancing vessels.........: " << argv[1] << std::endl;

try
   {
   VesselnessFilter->Update();
   }
catch( itk::ExceptionObject & err )
   {
   std::cerr << "Exception caught: " << err << std::endl;
   return EXIT_FAILURE;
   }

std::cout << "Writing out the enhanced image to " <<  argv[2] << std::endl;

typedef itk::ImageFileWriter< OutputImageType  >      ImageWriterType;
ImageWriterType::Pointer writer = ImageWriterType::New();

writer->SetFileName( argv[2] );
writer->SetInput ( VesselnessFilter->GetOutput() );

try
   {
   writer->Update();
   }
catch( itk::ExceptionObject & err )
   {
   std::cerr << "Exception caught: " << err << std::endl;
   return EXIT_FAILURE;
   }

return EXIT_SUCCESS;

}
   std::cerr << "Exception caught: " << err << std::endl;
   return EXIT_FAILURE;
   }
```

```
    return EXIT_SUCCESS;

}
```

References

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[4] R. Mannieshing, M.A. Viergever, and W. J . Niesse. Vessel enhancing diffusion: A scale space representation of vessel structures. *Medical Image Analysis*, 2006. (document), 1.1, 4